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**Abstract**

Rheology, the science of the flow and deformation of matter, can be applied to the workability of fresh mortars and the Viskomat is a commercially available instrument which is capable of measuring their rheological properties to a high degree of discrimination and sensitivity. Mortars conform to the Bingham model and require the measurement of both yield value and plastic viscosity to define their properties unambiguously. An experimental investigation of the effect of sand grading on four building mortars showed that yield stress and plastic viscosity were both reduced by increasing water content, but to a much lesser extent with the coarser sand. Sand grading and mix proportions interacted in a complex way and acted differently on yield stress and plastic viscosity, but this complexity presents possibilities for the control of mortar production.

## Introduction

Use of ready mixed mortar has advantages of convenience on site and the quality control of brickwork, but building sands are very variable and this can cause problems for producers in reliably producing mortars of high quality. The fact that quality control of concrete can be effected rapidly by rheological testing on the fresh mix suggests that the same may be done for mortars. This paper describes a suitable commercially available instrument and experimental method for the determination of the flow properties of mortar. Building upon a background of related work done on concrete materials it illustrates the effects of sand grading on mortar rheology and aims to demonstrate the potential application of rheological measurements in quality control.

## Rheological basis for the flow of materials

Rheology is the science of the flow and deformation of materials and is concerned with the interactions between shear stresses, shear strains and time. Its application to the workability of fresh concrete has been extensively documented [1,2], and it has been applied to mortar more recently [3].

For liquids and soft solids, such as suspensions, four simple and often encountered relationships between shear stress $\tau$ and shear rate $\gamma$ (flow curves) are sketched in Fig.1. The Bingham plastic model

$$\tau = \tau_O + \mu \gamma \tag{1}$$

applies to a material, such as fresh concrete or fresh mortar, which can resist shear stresses less than the yield stress $\tau_O$ without flowing but which at higher stresses shows a linear relationship between $\tau$ and $\gamma$, characterised by the plastic viscosity $\mu$. The yield stress results from forces of attraction between molecules or the solid particles in a suspension. Simple visual observation is often enough to confirm the existence of a yield stress: the material is able to support its own weight without flowing, such as on a trowel. In principle, two measurements at a different shear rates or shear stresses are sufficient to characterise a Bingham plastic, although more are preferred in order to reduce experimental errors.

The importance of this, termed the two-point principle by Tattersall [1], can be shown by reference to Fig. 2, which shows the Bingham flow curves of two mortars. Mortar A has a lower yield stress and a higher plastic viscosity than mortar B. If the workability of the two mortars are compared on the basis of a single measurement of shear stress at some fixed shear rate then the rank order will depend on the shear rate used in the measurement. Mortar A is stiffer (higher shear stress) at $\gamma > x$, while mortar B is stiffer at $\gamma < x$. When measurements are taken at $\gamma = x$ the mortars will be ranked as identical. Such considerations also apply to the conditions of use and mortar A could be self levelling (low yield stress) but slow moving, while mortar B would appear to be stiff at rest but would flow easily under the trowel.

In addition, Bingham plastics (including mortar [3]) often show structural breakdown under shear which requires that sample preparation, handling and testing techniques must be strictly standardised in order to produce yield stresses and plastic viscosities which are reliable indicators of the flow properties on a relative quantitative scale.

## Apparatus

The coaxial cylinders viscometer is an obvious instrument to consider for testing fresh mortar because the equations for flow can be expressed precisely in it, and Banfill demonstrated its feasibility [4,5]. However, practical difficulties associated with meeting the rules for reliable measurements make it necessary to consider non-ideal geometries, as was done by Tattersall for fresh concrete. He showed that is possible to test fresh concrete in a mixer and obtain information in a form related to that of a flow curve provided measurements are taken at more than one speed of mixing [1]. The Viskomat is a commercially available instrument[1] able to produce flow curves for mortar following the same principle. As shown in Fig. 3, it consists of a cylindrical container in which the mortar (about 1kg) is placed and which is mounted on a variable speed rotating turntable. A concentric paddle is mounted on a torque measuring head and as the cylinder rotates the viscous resistance of the mortar flowing through the blades of the paddle generates a torque. The torque is continuously monitored electronically as the sample is subjected to a predetermined speed and temperature programme over a given time as controlled by the software in a personal computer. While measurements are taking place all readings of torque, speed, temperature and time are filed by the computer for subsequent processing. On completion of the measurements the readings can be displayed or printed graphically or numerically by the menu driven software.

[1] Viskomat: Schleibinger Geräte, Haager Strasse 2, 8255 Schwindegg, Germany.

The flow curve can be plotted from the data in the form of torque, T, against speed, N, and it is found that mortars conform to the equation

$$T = g + h\,N \tag{2}$$

where g and h are constants characteristic of the material. According to a theoretical basis established by Tattersall [1] g is proportional to the yield stress and h to the plastic viscosity. The constants of proportionality can be determined following an experimental procedure described by Banfill [6] using model fluids of known rheological properties. Typical values of g and h for mortars are in the ranges 5-50 Nmm and 1-6 Nmms respectively which correspond to yield stresses and plastic viscosities of 40-400 $N/m^2$ and 1-5 $Ns/m^2$ respectively. These values can be determined with an experimental precision of typically ± 5%.

**Previous work on rheology of mortar**

Previous work has confirmed that mortar shows irreversible structural breakdown and that the downcurve conforms to the Bingham model [3]. This breakdown causes the torque on the inner cylinder or the paddle to decay exponentially with time at constant rotational speed. It also produces flow curves with hysteresis loops and the upcurve lies to the higher torque side of the downcurve. The structure can also be broken down during the mixing stage before the mortar is loaded into the test apparatus: more energetic mixing produces lower measured yield stress and plastic viscosity. Thus measurements of both the yield stress and plastic viscosity are needed, together with an indication of the previous shear history, or of the structural state of the material at the start of the downcurve. The mortar should preferably be completely broken down in order to produce unambiguous results. This corresponds to the situation in a mortar which has been mixed in an efficient and energetic mixer.

Table 1 is a summary of the effects of changes in composition of cement mortars using a siliceous sand with a maximum particle size of 1.18mm and when prepared following a standard procedure [3].

**Experimental programme**

The objective of the experiments described here was to investigate the effect of variations in the grading of the sand on the rheology of brickwork mortars.

Three sands were used in four mortar compositions with three water contents in a programme of 36 tests.The water contents were chosen to span the sensitivity range of the

Viskomat and to give consistence values in the range 10-15mm ball penetration [7]. The sands were produced by combining different proportions of each size fraction of a natural siliceous material to give the gradings summarised in table 2. Sand A corresponds fairly closely to the coarser of two sands used by De Vekey et al [8] but with slightly fewer particles coarser than 1.18mm. It is a type S sand under the British Standard classification [9]. Sand C corresponds to the finer of those used by De Vekey et al and is classed as type G. Sand B is of intermediate grading. Materials were batched by weight in the volume ratios given in table 3, calculated using their bulk densities. Mix 2 is the general purpose mortar suggested by the Building Research Establishment [10].

When preparing the mortars, the appropriate weight of each size fraction necessary to give 1000g of sand was combined in a single dry container. 250g of water was placed in the bowl of a 3 litre planetary action mixer and the correct weight of cement and lime, as appropriate, added. The slurry was mixed for 30 seconds at 120 rev/min. The sand was then added over a 60 second period with the mixer still operating. Finally the speed was increased to 280 rev/min for a further 60 seconds. When required, air entraining mortar plasticiser was dissolved in the mixing water at the manufacturer's recommended dosage for the weight of cement in the mix.

When mixed the mortar was immediately transferred to the sample container of the Viskomat, filling to the scribed level line. After lowering the paddle into the mortar the test routine (preloaded in the memory of the instrument) was started four minutes after adding the cement to the water. Speed increased from zero to 150 rev/min over 30 seconds, stayed constant for 60 seconds and decreased to zero again over 60 seconds. After testing, the mortar was returned to the mixer, an additional 10g water added and remixed for 30 seconds at 280 rev/min. It was then retested in the same way, remixed with a second increment of 10g water, retested and finally discarded. All tests were done at 20±2$^{o}$C.

## Results and preliminary discussion

Figs. 4a to 6b summarise the effect of water content on yield stress, g, and plastic viscosity, h, for each mix made with sands A, B and C. Unfortunately the corresponding values of consistence by dropping ball have been lost and cannot be reported here.

Not unexpectedly g and h both decrease with increasing water content. This is consistent with all previous results on the rheology of cement based materials. In this case the decreasing trend in both parameters is much less pronounced with sand A than with sands B and C. Thus a coarse sand makes a mortar less sensitive to changes in water content.

The fineness of the sand would be expected to affect the level of workability at equal water content and comparison of figs. 4a, 5a and 6a shows that g increases in the order of sand fineness A<B<C. This is consistent with the notion that yield stress is the result of forces of attraction between particles and that the finer those particles are, the greater the surface area for contact and the stronger the resulting material. However, in contrast the values of h pass through a peak (fig. 5b) with sand B, of intermediate grading, having the highest values of h and sands A and C (figs. 4b and 6b) giving approximately similar values. This echoes results with other (non cement-based) suspensions which show that the rheology is affected in a complex way by the particle size distribution of the dispersed solid. Thus sand grading influences g differently from h and the changes are broadly in line with those summarised in table 1, which was prepared from separate tests on the various parameters and not, it must be emphasised, from tests on building mortars. The more complicated trends observed here reflect interactions between sand grading and the presence of lime and/or entrained air.

The rank order of the mixes changes for the different sands. Thus the general order of yield stress g for sand A is mix 3>1>4>2, but 1>3>4>2 for sand B and 3>4>2>1 for sand C. For plastic viscosity h the general order is 3>4>2>1 for sand A, 3>1>4>2 for sand B and 1>2>3>4 for sand C. There is clearly a significant interaction between the effect of the grading of the sand and the mix proportions on workability. In addition the two workability parameters are affected in a different way: the rank order of the yield stresses is different from that of plastic viscosities. Thus variation in grading of the sand can have an unpredictable effect on the workability of mortar. This rheological test can demonstrate this clearly.

Despite the similar trends of water content on g and h fig. 7 shows that there is only a weak overall correlation between g and h (correlation coefficient 0.29). This confirms the necessity of applying the two point principle to mortar. To characterise mortar unambiguously requires both parameters to be measured, and this is not just to comply with what might be seen as a pedantic scientific principle. The discussion of fig. 2 above showed that it is possible to be misled by a single measurement of some flow related property carried out on two different mortars, but the important practical point demonstrated by these real building mortars is that it is not possible to predict the value of one parameter from the other: both must be measured, and the Viskomat offers a convenient way of doing this.

**General Discussion**

Closer examination of fig. 7 shows that the results for sand C, the finest of the three, are grouped to the right of the graph, i.e. they tend to have higher values of g with low to medium values of h. In contrast, results with sands A and B are grouped towards the left of the graph. Recognising that water content affects both g and h in the same sense (note the distribution of points, broadly radiating from the origin on fig. 7) this suggests that for these mixes the effect of water content and sand grading can be summarised as shown in fig. 8. The implications of this for the quality control of mortar production should be considered.

Assume that the combination of g and h specified for a particular mix is given by point O on fig. 8, which is strictly speaking an area centred on O and bounded by appropriate tolerances. If the sand gets finer during a run of production the measured g and h move from O to point P. This is probably perceived as a stiffening (increase in g) by the mixing plant operator who is only able to do a subjective assessment of flow at low shear rate. Further, if the control is such that the operator is only able to change the water content then additional water to compensate for this change will move the measured g and h from P in a direction which parallels the radial trend shown by increasing water content, i.e. to point R. Mixes R and O differ in h and therefore show different flow behaviour, so that compensating for finer sand by adding more water cannot reproduce the original specified mix. Instead more complicated changes might have to be made and it would be necessary to obtain data for the mortar concerned, possibly using table 1 as a starting point.

These changes could not be detected by a single point test which, if it operated at low shear rate, would rank mortars O and R as identical (see fig. 2) and their different flow properties might cause a problem in a practical situation such as pumping where resistance to flow at higher shear rate is important. It might be argued that in some applications it is only the level of g that is important for workability. However, work with concrete has shown that at low values of g the value of h is related to the tendency for segregation and bleeding and this suggests that a two point test for mortar could give additional useful information.

In many mixers it is not possible to take a sample to carry out a batch workability test before the mortar is discharged. In such situations an on-line within-mixer test would be useful and rheology suggests a way of doing this. Such a test could not be based on measuring the power consumption during mixing, as has sometimes been attempted, because the overwhelming contribution of the inertia of the rotating parts of the machinery would mean that the effect of variations in the mortar's behaviour would be insignificant. Additionally, of course, measurements would be needed at two or more speeds of rotation to give the necessary two constants and this would be impracticable. Instead simultaneous measurements of shear stress could be made by mounting pressure transducers to measure shear stress at locations within the mixer where the linear velocity and hence shear rate are different. It would be simple to use the data so produced in a small computer program to calculate g and h against the specified values. If the values fall outside a preset tolerance then the computer would suggest corrective action or even, by a feedback loop, take that action itself. All that would be needed is to produce charts like fig. 8 from experimental work on the standard mixes used in a particular plant and load the information into the computer. Alternatively a simple visual chart could be used, but the whole approach is only possible because of our knowledge of the rheology of mortars. Charts like fig. 8 have been produced and employed successfully in concrete production [1].

## Conclusion

Fresh bricklaying mortars conform to the Bingham model and to define them it is necessary to measure the yield stress and plastic viscosity, which the Viskomat is able to do to a high degree of sensitivity and discrimination. Using it to determine the rheological parameters of mortar will help in the selection of raw materials and development of formulations. The complex way in which composition affects rheology offers possibilities for the quality control of mortar production.

## Acknowledgements

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**Captions to figures**

1. Common flow curves for liquids.

2. The two point principle applied to Bingham flow curves of two mortars.

3. Schematic diagram of Viskomat (dimensions in mm).

4a. Effect of water content on g for sand A.

4b. Effect of water content on h for sand A.

5a. Effect of water content on g for sand B.

5b. Effect of water content on h for sand B.

6a. Effect of water content on g for sand C.

6b. Effect of water content on h for sand C.

7. Relationship between g and h (all results).

8. A summary chart for mortar.

**Table 1**

**Summary of effects on cement-sand mortar**

| Change | Effect on: Yield value | Effect on: Plastic viscosity |
|---|---|---|
| Increase water content | decrease | decrease |
| Increase sand content | increase | increase |
| Increase cement content | increase | increase |
| Increase fineness of sand | increase | increase/no change |
| Add plasticiser | decrease | no change |
| Add air entrainer | no change | decrease |
| Replace part of cement with: | | |
| flyash | decrease | decrease |
| microsilica | increase | decrease |

**Table 2**

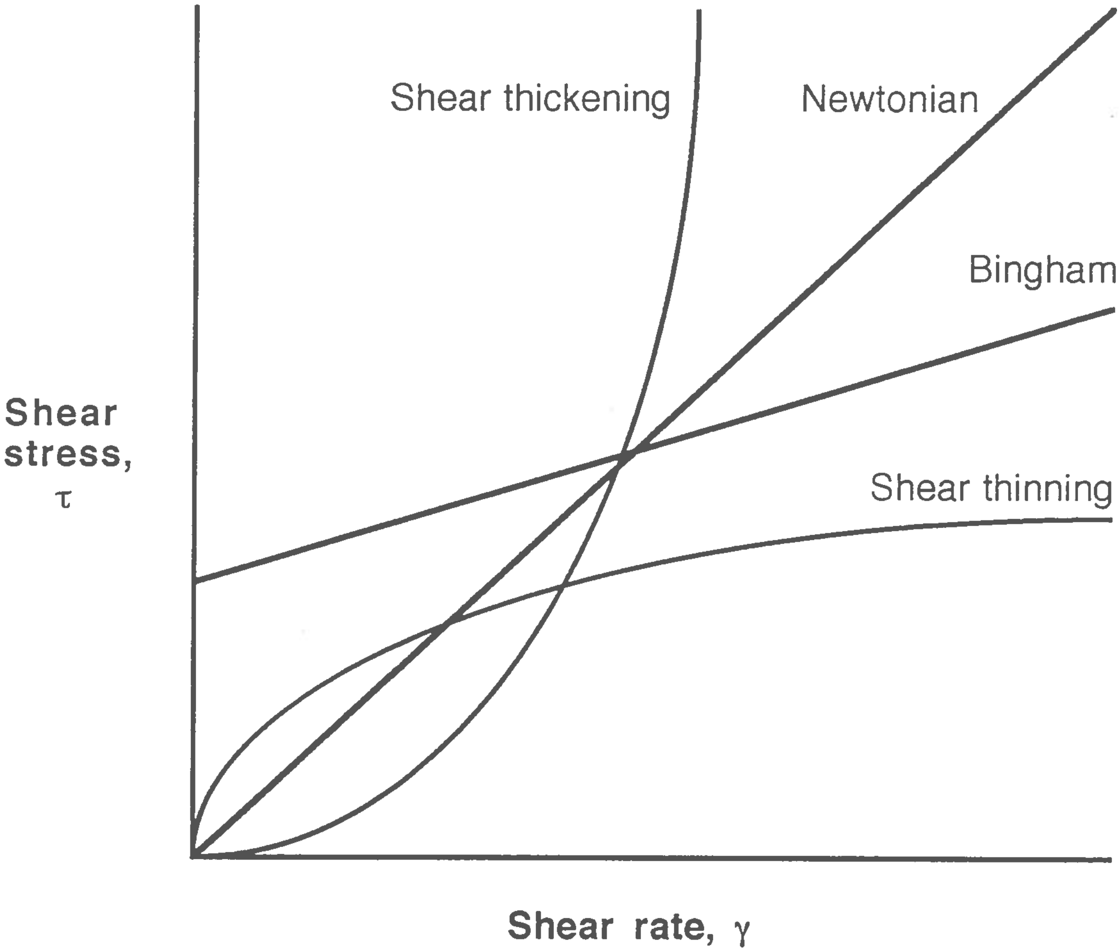
**Particle size distribution of the sands (% passing)**

| Sieve size | Sand A | Sand B | Sand C |
|---|---|---|---|
| 5 mm | 100 | 100 | 100 |
| 2.36 | 99 | 99.5 | 100 |
| 1.18 | 87.5 | 95.5 | 100 |
| 600 μm | 75 | 91.5 | 97.7 |
| 300 | 34.5 | 58.5 | 76.5 |
| 150 | 7 | 7.5 | 9.5 |
| 75 | 1 | 1 | 1 |

**Table 3**

**Composition of building mortars tested**

| Mix | Cement | Masonry cement | Lime | Sand | Plasticiser |
|---|---|---|---|---|---|
| 1 | 1 | - | 1 | 5.5 | |
| 2 | 1 | - | 1 | 5.5 | Yes |
| 3 | 1 | - | - | 5.5 | Yes |
| 4 | - | 1 | - | 4.5 | |


Shear thickening
Newtonian
Bingham
Shear thinning
Shear stress, τ
Shear rate, γ

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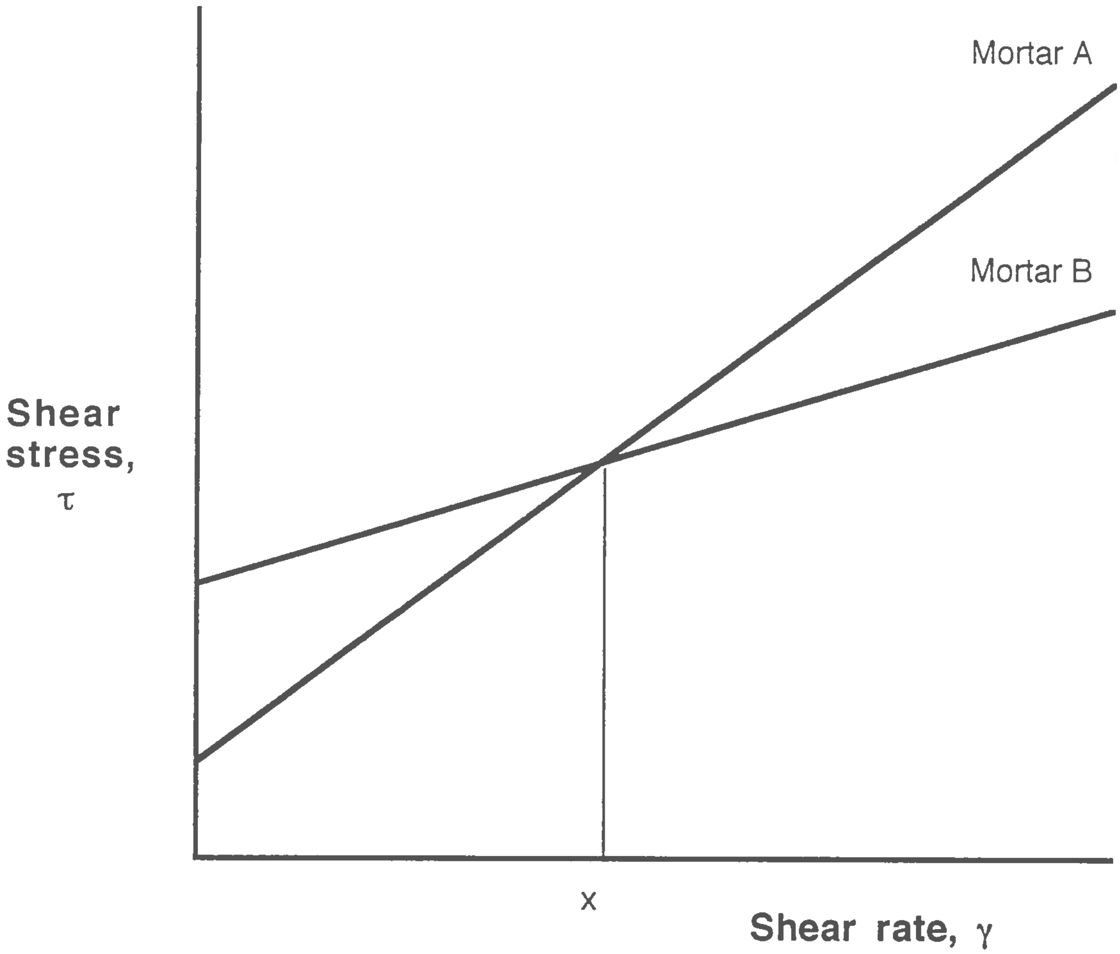
Mortar A
Mortar B
Shear stress, τ
x
Shear rate, γ

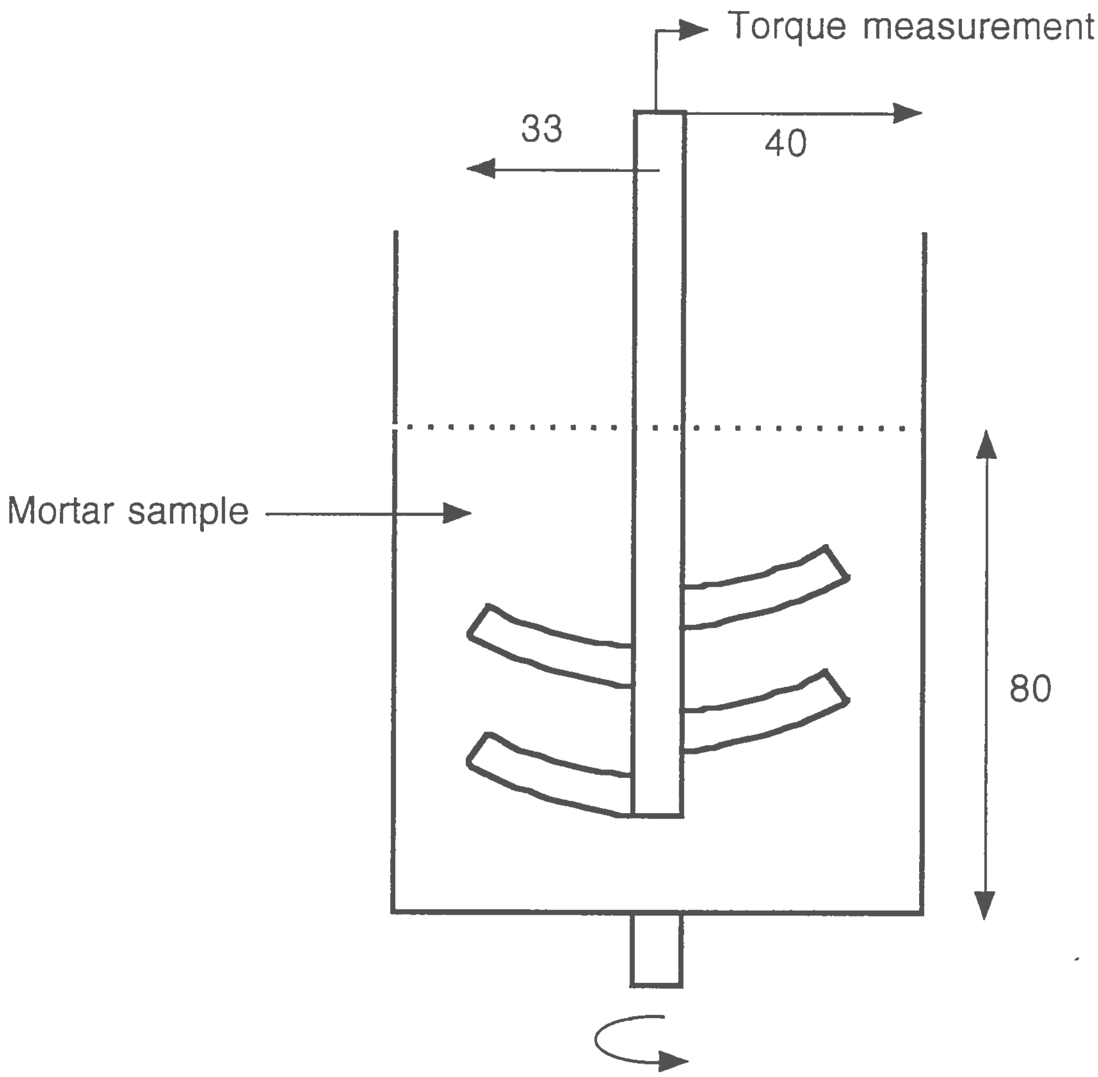


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Fig. 3

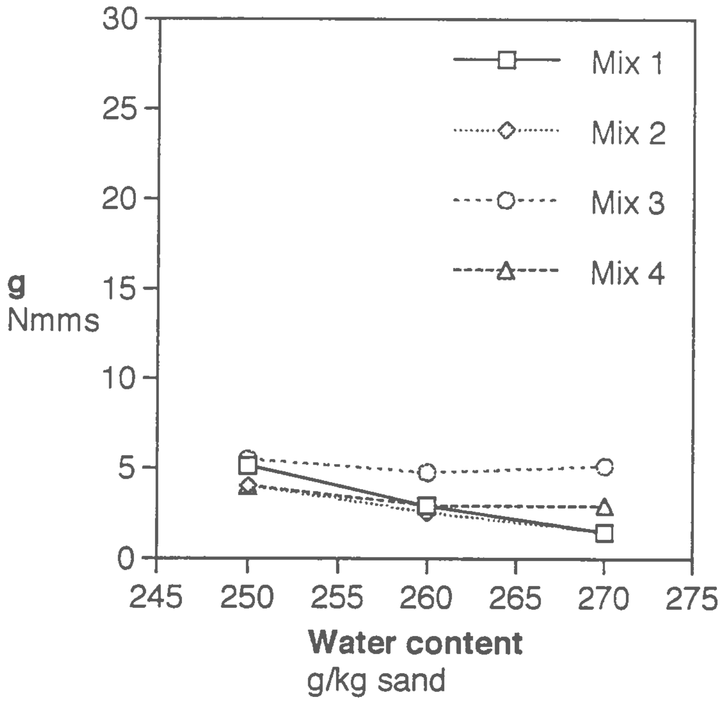


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Fig 4a

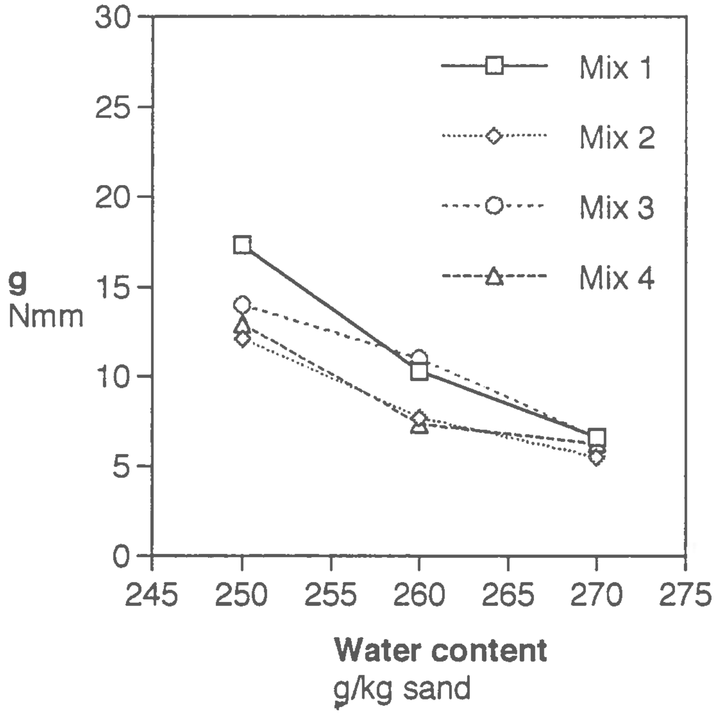


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Fig 5a

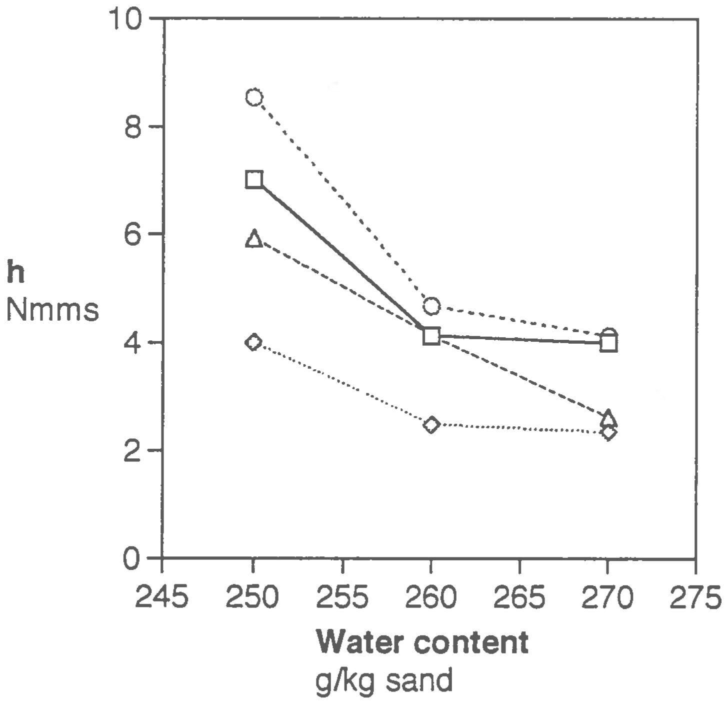


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Fig 5b

Fig 5a

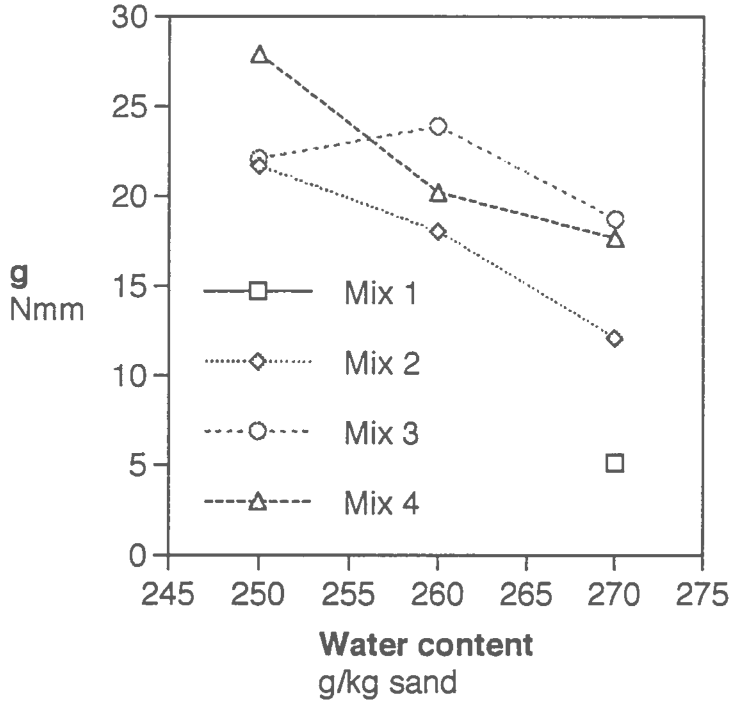


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Fig 6a

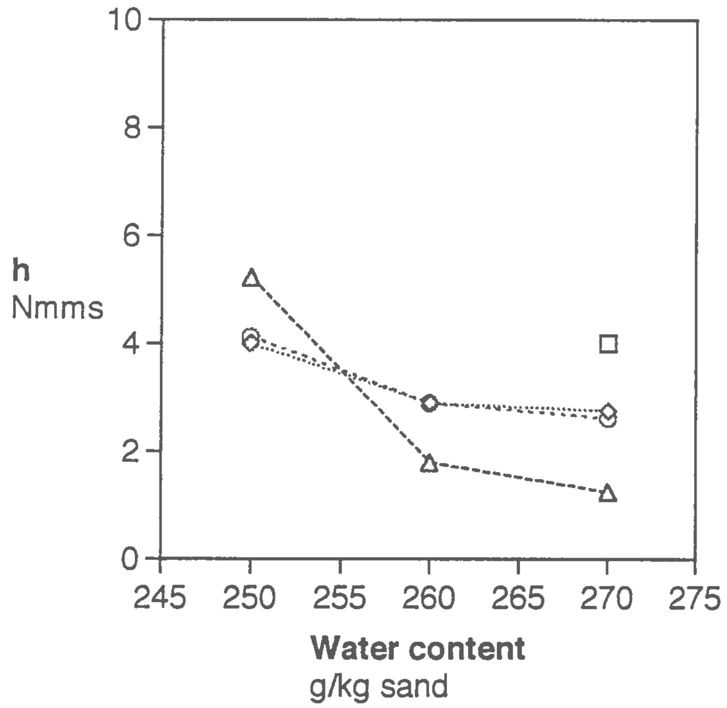


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Fig. 6b

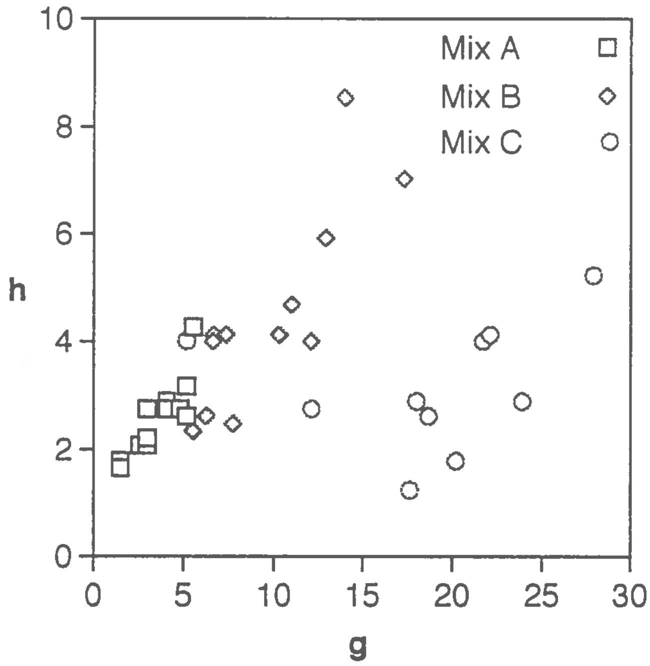


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Fig. 7

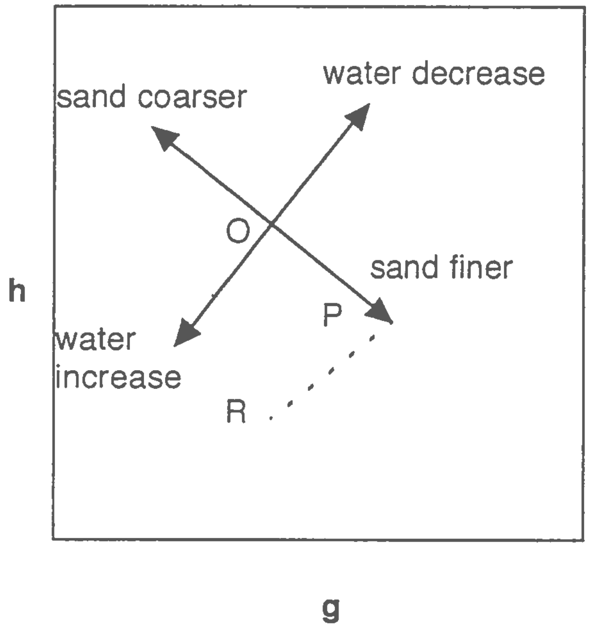


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Fig 8